Combining Probabilistic Shaping and Nonlinear Mitigation: Potential Gains and Challenges

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Abstract: We experimentally compare different options for transmission at 200G net bit-rate and demonstrate that the benefits of probabilistic shaping and nonlinear mitigation via SRO and/or DBP can be effectively combined to enable propagation reach enhancement of $>40\%$.
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1. Introduction

In the last few years, the quest for increasing the capacity of single-mode optical communication systems has seen notable developments, with advanced techniques for signal transmission and detection being proposed and demonstrated. Since they set the ultimate capacity limits, fiber nonlinearities have motivated a great effort both on the development of digital compensation algorithms [1] and on the design of optical signals with enhanced nonlinear robustness [2]. Intra-channel digital back-propagation (DBP) has been a topic of extensive research, enabling SNR gains of up to $\sim$1 dB [3], or equivalently $\sim$25% reach increase, at the expense of substantial additional complexity at the DSP level. To combat nonlinearities while alleviating the burden on the DSP side, symbol-rate optimization (SRO) using electronic subcarrier multiplexing signals has been shown to provide effective gains in signal reach, typically in the range of 10-20% [2]. In addition, it has also been demonstrated that the gains provided by DBP and SRO can as well be combined to enable further nonlinear mitigation [4].

More recently, the development of capacity achieving modulation schemes, such as probabilistic shaping (PS), has become a key topic of research, mainly due to inherent shaping gains of typically $\sim$1 dB that have been experimentally demonstrated [5]. However, one of the topics of more controversy in this area has to do with its performance in mildly nonlinear regime (at the optimum power) over long-haul distances. According to several high-performing nonlinear models [6, 7], the Gaussian-like distribution of PS signals is more prone to the generation of nonlinear phase noise (NLPN) which may bring substantial performance penalties.

In this paper, we experimentally compare different options for the transmission at 200G over ultra-long-haul distances, resorting to PS, nonlinear mitigation via SRO/DBP and combinations of these techniques. Our findings show that the benefits of PS and SRO can be effectively combined, provided that NLPN is properly compensated.

2. Experimental setup and results

The experimental setup utilized in this work is depicted in Fig. 1a. We transmit 21 channels in 50 GHz slots, each operating at per-λ rate of 32 GBaud, corresponding to $\sim$1 THz of total optical bandwidth. From the total baud-rate we reserve 20% overhead for SD-FEC and additional 8% for other protocol overheads, yielding 25 GBaud net baud-rate. Then, to modulate the transmitted polarization-multiplexed signal we consider either 16QAM or PS-36QAM (which, at 200G, was found to provide very similar shaping gain to higher-order constellations). In both cases we additionally consider two types of signals: single-carrier or multi-subcarrier (MSC) composed of 4 subcarriers, $N_{\mathrm{SC}} = 4$.

The channel under test (CUT) is generated by an external cavity laser (ECL) and optically modulated in a dual-polarization Mach-Zehnder modulator (DP-MZM), which is electrically fed by a 64 Gsa/s digital-to-analog converter (DAC). The remaining 20 optical channels are divided into groups of odd and even carriers and are generated by distributed feedback lasers (DFB). These interfering channels are then modulated by two independent single-polarization Mach-Zehnder modulators (SP-MZM) fed by a second DAC identical to the first one. A polarization multiplexing emulator (PME) consisting of an optical delay line is then utilized to generate the dual-polarization interfering channels. The recirculating loop is controlled by acousto-optic modulators (AOM) and is composed of 4 spans of pure silica core fiber (PSCF) with 108.25 km ($\alpha = 0.162$ dB/km, $D = 20.12$ ps/nm/km and $\gamma = 0.8\ \mathrm{W}^{-1}\mathrm{km}^{-1}$) each and EDFA-only amplification with $\sim$5 dB of noise figure. A gain equalization (GEQ) filter is employed to flatten the EDFA gain, and a loop-synchronous polarization scrambler (LSPS) is utilized to provide more realistic polarization

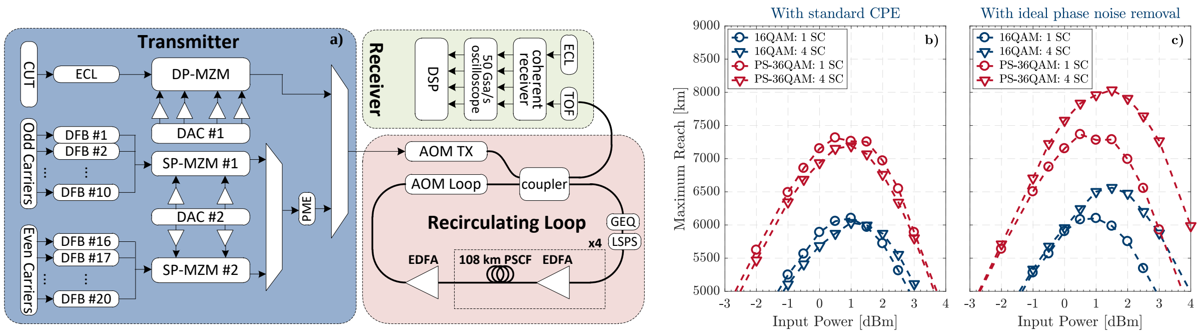

Fig. 1: a) Experimental setup; b) Maximum reach with 1 and 4 subcarriers using standard CPE and c) Ideal phase noise removal.

statistics. Before the receiver, a tunable optical filter (TOF) is utilized to filter out the interfering channels. After coherent detection, the signal is sampled by a 50 Gsa/s oscilloscope and DSP is then applied offline. The DSP includes standard subsystems for adaptive equalization (51 taps), frequency offset removal and carrier-phase estimation (CPE) based on a dual-stage blind-phase search (BPS) and maximum likelihood CPE [8] with an optimized number of taps. Finally, the system performance is measured in terms of mutual information (MI). A MI threshold of 10/3 is defined for post-FEC error-free operation (considering ideal SD-FEC).

The estimated maximum reach obtained for 16QAM and PS-36QAM with 1 and 4 subcarriers are shown in Figs. 1b and 1c, corresponding to two distinct phase noise compensation approaches: i) a decision-directed BPS-ML CPE [8] with optimized number of taps to yield maximum performance and ii) an ideal phase noise removal (IPNR) approach based on fully data-aided BPS-ML CPE with optimized number of taps to yield maximally circular constellation points, following the same procedure as in [4]. The results of Figs. 1b and 1c allow to draw two main conclusions. First, we observe that with single-carrier transmission (32 GBaud) the decision-directed BPS-ML CPE yields very similar performance to that of the IPNR approach, which evidences that NLPN can be effectively compensated over single-carrier transmission using standard CPE algorithms, requiring only a simple optimization of the CPE block length. Second, we conclude that with 4 subcarriers (8 GBaud per subcarrier) the standard decision-directed BPS loses its ability to track and remove NLPN both for the 16QAM and PS-36QAM cases. This penalty is caused by the loss of temporal resolution with decreasing symbol-rate (increasing symbol period) suffered by traditional CPE algorithms working at 1 sample/symbol. As the ratio between NLPN correlation time and symbol period becomes smaller, the number of taps required for its compensation is also reduced proportionally. However, on the other hand, it is well known that CPE requires a sufficiently large number of taps to average out the effect of additive ASE noise. Consequently, as the symbol-rate is reduced, the optimum CPE length starts becoming dictated by the ASE noise averaging requirements, thereby losing the ability to track and remove NLPN. This challenging issue of NLPN compensation for MSC signals has already been reported in several experimental campaigns [4], and remains an active topic of research regarding the development of advanced joint-subcarrier CPE algorithms [9]. In this work, rather than investigating on enhanced CPE techniques, we aim at assessing the ultimate performance gains that can potentially be achieved from effective NLPN compensation, using for that purpose the IPNR ideal approach.

In Fig. 2a we compare the obtained experimental results in terms of maximum reach at the optimum launched power against the estimations provided by enhanced Gaussian noise (EGN) model [6]. To correct for the Gaussian assumption of the standard GN model, the EGN includes correction factors that depend on the fourth and sixth moments of the transmitted constellation, thereby enabling to capture the modulation format dependence of nonlinearities. Previous works have demonstrated that NLPN is essentially a phenomenon of conversion from amplitude modulation (AM) to phase modulation (PM) [7]. For that reason, optical signals with constant envelope, such as QPSK, are known to generate very small amounts of NLPN [7]. In contrast, higher-order QAM formats and/or probabilistic shaped constellations generate strong NLPN through AM-PM conversion, approaching the pessimistic Gaussian assumption of the GN model. Therefore, if we assume that NLPN can be effectively removed by CPE, as it seems to be the case for single-carrier transmission, then the nonlinear performance of the system can be regarded as being modulation-independent, thus being accurately modeled by the EGN with correction factors corresponding to a constant envelope constellation (EGN_{CE}) [10]. Based on this reasoning, the shaded areas in Fig. 2a show the expected maximum reach regions, which are: i) lower bounded by the EGN model estimation using correction factors corresponding to the actual transmitted constellation, thus assuming that NLPN cannot be removed by CPE, and ii) upper bounded by the EGN_{CE} using correction factors corresponding to a constant envelope constellation, which instead assumes that NLPN can

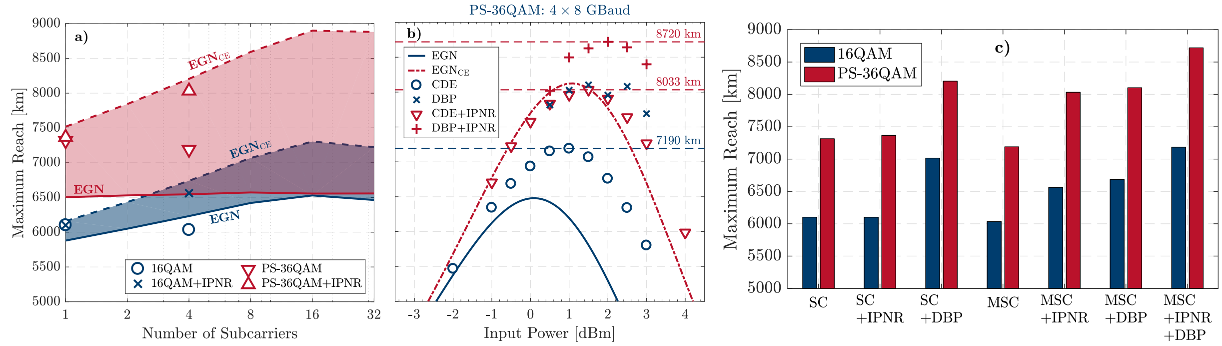

Fig. 2: a) Maximum reach at the optimum power versus number of subcarriers, using 16QAM and PS-36QAM modulation; b) Maximum reach versus input power for the case of PS-36QAM with 4 subcarriers; c) Summary of maximum reach results for all considered scenarios.

be fully removed by CPE. The extension of the shaded areas in Fig. 2a clearly shows that the impact of NLPN is potentially stronger over the PS-36QAM constellation, due to its more "Gaussian-like" distribution. It is interesting to note that, if NLPN is not compensated at all, the shaping gain of $> 20\%$ in maximum reach (gap between the EGN_{CE} dashed lines) can be more than halved in the single-carrier case (gap between the EGN solid lines) and even completely eliminated for the multi-carrier case with $N_{\text{SC}} \geq 16$. The experimental results with 1 and 4 subcarriers obtained with the IPNR approach tend to corroborate the EGN_{CE} estimation. Instead, using the standard decision-directed CPE, the obtained maximum reach results tend to converge to the more pessimistic EGN estimation, confirming the inability for NLPN compensation at lower symbol-rates. Note that, according to the EGN results, the maximum benefit from SRO could be obtained at around 16 subcarriers (2 GBaud per subcarrier), which would enable to almost double the SRO gain obtained at 4 subcarriers (from $\sim$10% to $\sim$20%). However, due to practical limitations in our setup, we have found increased linear penalties for $N_{\text{SC}} > 4$, which has prevented a fair comparison with the reported results.

Alternatively to SRO-based nonlinear mitigation, we also investigated the performance benefits that can be enabled by intra-channel DBP (8 steps/span) over all considered modulation schemes. The results shown in Fig. 2b, obtained for the specific case of 4×8 GBaud PS-36QAM, show that the gains provided by DBP over chromatic dispersion equalization (CDE) are actually very similar to those achievable via SRO aided by IPNR. The choice between these two nonlinear mitigation options then mostly depends on practical implementation aspects, such as feasibility and complexity. Provided that IPNR is applied, in Fig. 2b we demonstrate that the gains of SRO, DBP, and PS can effectively be combined to achieve a maximum reach of $>$8700 km, a $\sim$42% increase with respect to the baseline single-carrier 16QAM scenario. The relative merits of SRO, DBP and PS are finally summarized in Fig. 2c. The main conclusions that can be drawn from this overall picture are: i) standard CPE is able to almost ideally compensate for NLPN over single-carrier signals; ii) advanced NLPN mitigation algorithms that can approach the IPNR performance are a key requirement to enable SRO over MSC signals; iii) acting alone, PS, DBP and SRO provide comparable gains of $\sim$10-20% reach increase, while the combination of these techniques can yield $>$40% reach gain.

3. Conclusions

We have experimentally demonstrated that the benefits of PS, SRO and DBP can be combined for ultra-long-haul 200G transmission, yielding more than 40% overall reach increase. The main challenge to achieve these potential performance gains lies on the development of effective NLPN compensation algorithms over multi-subcarrier signals.

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